# TECHNICAL REPORT

## Use of Commercial-Off-The-Shelf Vehicles for Towed Array Magnetometry: *Geophysical Procedures for Vehicle Signature Measurement*

## ESTCP Project MM-0605

October 2007

**Mr. Robert Siegel**
SAIC
7 Wells Avenue,
Newton, MA 02459

Approved for public release; distribution unlimited.

Environmental Security Technology Certification Program

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**OCT 2007** | 2. REPORT TYPE<br>**N/A** | 3. DATES COVERED<br>**-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Use of Commercial-Off-The-Shelf Vehicles for Towed Array Magnetometry: Geophysical Procedures for Vehicle Signature Measurement** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**SAIC 7 Wells Avenue, Newton, MA 02459** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **SAR** | **17** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

# ESTCP Project MM-0605:
# Use of COTS Vehicles for Towed Array Magnetometry

## Report on Filtering Vehicle Magnetic Signature

Rob Siegel
SAIC

10/15/2007

The $1/R^3$ sensitivity of total field magnetometers makes them highly sensitive to any nearby ferrous metal, including that of a towing vehicle. The magnetic signature of a vehicle varies primarily with the orientation of the vehicle in the Earth's magnetic field. It also varies with the orientation of the sensor array relative to the tow vehicle (ie in a tight turn, the sensor array is no longer directly behind the vehicle). In addition, if the vehicle signature is very high and / or the sensor array is very close, small changes in vehicle pitch and roll and sensor array pitch and roll will engender changing amounts of vehicle signature in the data that for practical purposes cannot be filtered out. For the sake of this discussion, we are assuming that the vehicle is far enough away that the primary effect in the data is from changes in vehicle orientation relative to the Earth's magnetic field. When surveys are conducted in a bidirectional up-and-back fashion, the "bulk signature" of the vehicle is readily seen as differences in magnetic background between outgoing and incoming traverses. These differences (offsets) create stripes or streaks in the data along the direction of travel. Because a GPS antenna is frequently employed in towed array magnetometry, the GPS antenna signature is sometimes seen as an additional streak over the center magnetometer. Simple background leveling techniques used to remove the magnetic signature are not trying to model the vehicle's signature, and thus they usually remove both the vehicle signature as well as the offset caused by the GPS antenna. Depending on the signature removal technique, it may also remove diurnal drift of the Earth's magnetic field and long-wavelength geology.

The vehicle signature removal techniques we have employed fall into four categories:

- Static offset removal
- Table-based offset removal (the Corps' octant test)
- Directionally-dependent offset removal
- Time-domain filtering (dynamic background leveling)

For most of the discussion below, we use the test set of data acquired for this project last year with the Polaris Ranger (figure 1) at the Devens test site. While the Polaris Ranger does not have the lowest possible signature and thus is not necessarily the vehicle that we would purchase, it is a vehicle with a bulk signature at the lower end of the ten vehicles tested (though higher than both the original aluminum VSEMS dune buggy and the aluminum-framed Bobcat / Club Car vehicles). The vehicle-to-magnetometer separation

currently employed on VSEMS is 15 feet. Because we wish to tow the VSEMS platform with a candidate vehicle, the vehicle-to-magnetometer separation of most interest is this 15 foot separation. At this distance, the bulk offset between North-going and South-going traverses for the Polaris Ranger was 24 nT. Thus, the Ranger represents a vehicle with a signature that, while still moderately low, stresses the signature removing techniques more than the VSEMS buggy (2 nT at 15') or its likely replacement, the Club Car diesel (8 nT at 15').


**Figure 1: Polaris Ranger towing the TSEMS mag/EM platform at the Devens test site in 2006**

We try to show, below, the effect of each of these techniques on the same set of data, but that is difficult for the following reason. The main technical approach of this effort has been to measure bulk signature by actually towing a small magnetometer array behind ten separate vehicles, varying the vehicle-to-magnetometer separation from 20' to 15' to 10' to 5', and conducting area surveys at each separation instead of relying on static octant tests of the form required by the Corps of Engineers. Because the project emphasis was on area surveys, the octant tests we conducted last year were conducted only at 10' vehicle-to-magnetometer separations, not at the 15' separation used on VSEMS, or at the 5' and 20' separations. Thus, while we would prefer to concentrate on 15' data, the ability to apply corrections generated from octant data exists *only* for 10' data, even though the 10' vehicle-to-sensor separation is aggressively close. For this reason, below we take the approach of using 10' data to do an "apples to apples" comparison of octant, directional dividing, and median filtering, but we use the more realistic 15' data to compare different median filter windows.

Lastly, we present some older data taken at the APG open field site with an earlier version of VSEMS in 2004 using the now-retired fiberglass platform that had the magnetometers 10’ from the aluminum tow vehicle, and show the differences between unfiltered, directionally-divided, and filtered data.

**Static Offset Removal**

If the signals from the magnetometers have fixed offsets relative to each other, and if those offsets do not change with survey direction, and if the survey direction does not change, the offsets can simply be calculated and subtracted. However, while EM61s may be “zeroed” in this fashion for short surveys, this is rarely the case for magnetometer surveys since the physics of magnetometry guarantees that the offsets *will* change along with changing direction. If all traverses in a magnetometer survey were acquired in the same direction, this would be possible, but that is an unrealistic constraint for anything except prove-outs, and as such we will not deal with it here. Static offset removal, however, is used in conjunction with both octant corrections as well as directional dividing; these are described below.

**Table-Based Offset Removal (Octant Test)**

One of the Corps’ DID requirements for magnetometry is to conduct an octant test, orienting the vehicle North, Northeast, East, Southeast, etc, and measuring the static offsets at these orientations. From these measurements, a table can be built that represents the offset for each magnetometer at each of eight discrete orientations. This table can then be interpolated to provide offset as a function of measured heading. When the data are processed, the heading obtained from the GPS can then be used to look up the correction.

Our experience is that while the static octant test generates at-a-glance results showing the expected effect of the vehicle, it is not a great tool to actually remove streaks along the direction of travel from dynamic survey data. This is due to a number of factors, including the difficulty in finding a truly magnetically clean area in which to do the octant test. This is exacerbated by having a wide array. That is, when doing the octant test with a man-portable system employing a single magnetometer, the magnetometer can be fixed and the system rotated around it, but when using a five magnetometer wide array with a 2.5 meter swath width, when the entire system is moved to the next octant line, the center magnetometer must be parked as close to the same location as possible, but the other magnetometers certainly *have* moved, and any local geology or clutter will affect the results. Originally we thought that a *circle* test would be better than an *octant* test (i.e., locate a magnetically clean area and simply drive the system around in a big circle to directly generate offset as a function of heading), but it is virtually impossible to locate a large circular area completely free of clutter and geology. The circle data are good for *showing the effect of changing heading*, but not ideal for removing the effect.

During vehicle evaluation for this project last year, octant tests were conducted for all vehicles at a mag-to-vehicle separation of 10’, which was intended to provide apples-to-apples octant measurements across all vehicles. It was not intended to provide data for

static signature removal, as 10’ is probably too close for anything other than aluminum-bodied vehicles. However, the results are surprisingly good owing to the small size of the survey and the uniform directions of the traverses.

For the Polaris Ranger at 10’, the octant test produced the following results (shifted so the smallest reading is leveled to zero):

| Direction | Mag A | Mag B |
|---|---|---|
| N | 30.68 | 32.91 |
| NE | 5 | 0 |
| E | 22.34 | 4.8 |
| SE | 78.02 | 56.03 |
| SE | 112.12 | 106.49 |
| SW | 77.59 | 88.19 |
| W | 25.66 | 32.86 |
| NW | 31.05 | 31.22 |

**Figure 2: Octant Test Results for Polaris Ranger, 10' Separation**

This shows a peak-to-trough variation of 112 nT. These results are plotted in the figure below. Results for the two magnetometers on the platform are plotted individually. The directions are plotted with North as the left-most abscissa and increasing clockwise through Northeast, East, etc.

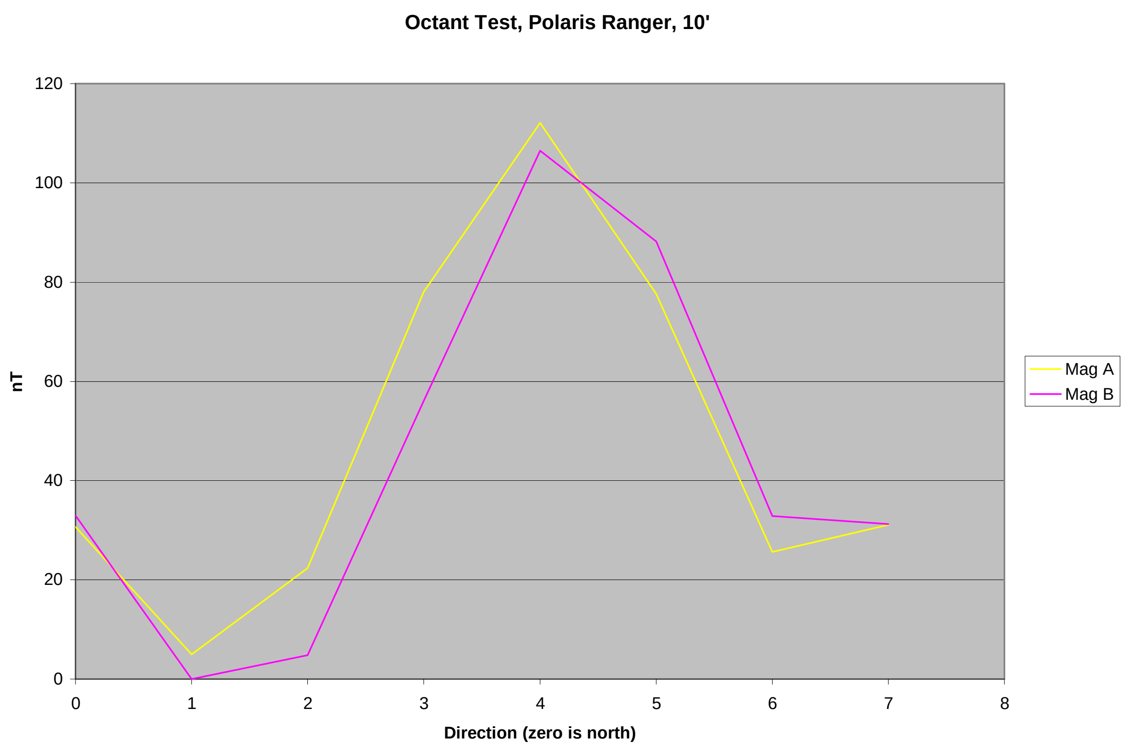


**Figure 3: Plot of Octant Test Results, Polaris Ranger, 10’ Separation**

Image data obtained using the octant test corrections are displayed below. The image on the left below is unfiltered data. The image on the right has had the directionally-dependent offsets from the octant tests applied.

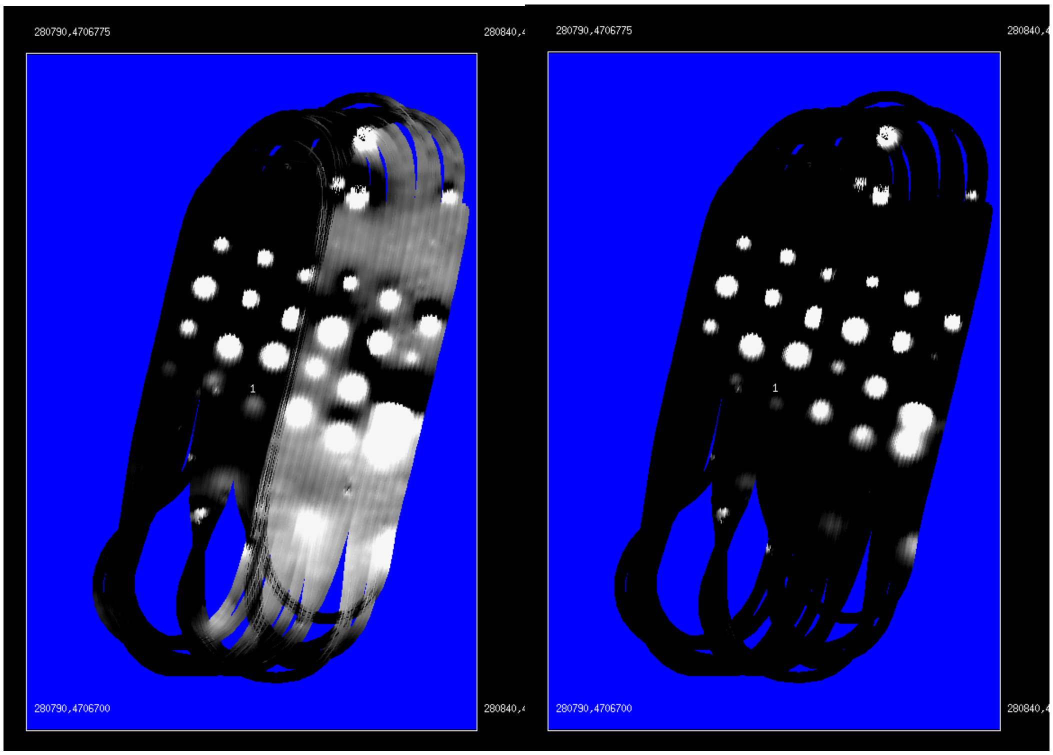


**Figure 4: Polaris Ranger, 10' Separation, Uncorrected (left) and Corrected with Octant Data (right), +- 50 nT**

Obviously the effect of shifting the minimum correction to zero had an undesirable gross leveling effect. Correcting the data set so the background is at zero results in the image below, left. The gross directional effects of the vehicle have been corrected (perhaps remarkably so, considering that the magnetometers are just 10’ behind a COTS vehicle, not a custom aluminum vehicle), but two problems are evident. First, the correction is breaking down on the south part of the data set where the vehicle is turning around (dark streaks). Second, there is “corduroy” in the data set – fine lines along the direction of travel that has as much to do with the offset from the GPS antenna as it does with the vehicle. We can attempt to correct this using a static correction – data in the yellow area of interest below are averaged for each magnetometer, and the average values are then subtracted. The corrected data is shown on the right, and it can be seen that the correction essentially just moves the streaks to the other side of the image. Even though this is an extreme case, it is typical in our experience – data from the octant test alone is rarely enough to correct VSEMS array data and generate streak-free images.

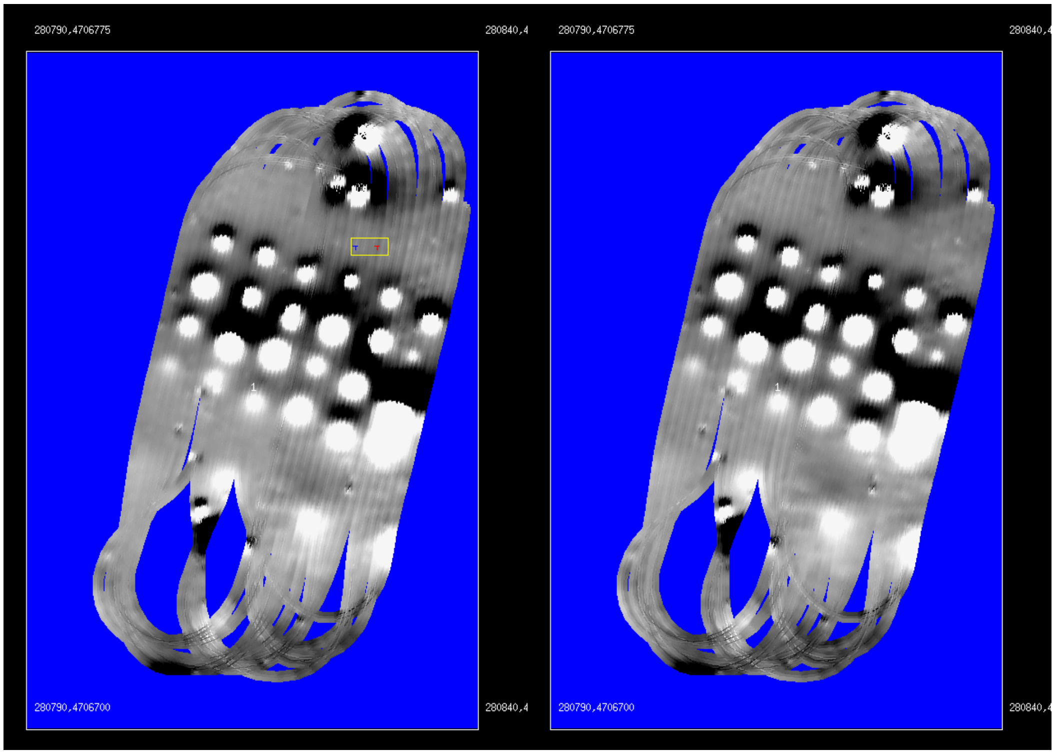


**Figure 5: Polaris Ranger, 10' Separation, Corrected with Octant Test Data (left), and Further Corrected in an Attempt to Remove Streaks (right), +- 50 nT**

### Directionally-Dependent Offset Removal (Directional Dividing)

Because many surveys have predominant traverse directions, it is possible to divide the data into like-going traverses, calculate the offsets above background for each sensor for each direction, offset-correct each direction and sensor individually, and then merge the data back together. SAIC used this technique extensively for years on STOLS and VSEMS surveys. A predominant set of directions are entered (e.g., North and South), along with an acceptance tolerance (e.g., 15 degrees) into a piece of software that sorts the data into files of like direction. Data for each direction is then processed, viewed, corrected, and reprocessed individually. To correct each directional set, the operator manually draws an area of interest in a region of the data seen to have the “corduroy” effect but no anomalies. The software then accumulates the data for each sensor in this area of interest, and saves the average for each sensor. The data are then reprocessed with the offsets separately subtracted out for North-going and South-going traverses, background-leveling the data. A directionally divided set is shown in the image left below. Note that the “turnarounds” have been chopped out of the data since they fall outside a 15 degree acceptance window centered at North and South. Corrected data are shown in the image on the right, which is of remarkably high quality considering that the magnetometers are only 10’ from a COTS vehicle. Our experience is that this technique produces cleaner, less streaky data than the table-based technique because it is using actual dynamic survey data (not previously-collected static data) to calculate the offsets. However, the correction itself is, in fact, static – it is not “tracking” the data in any way.

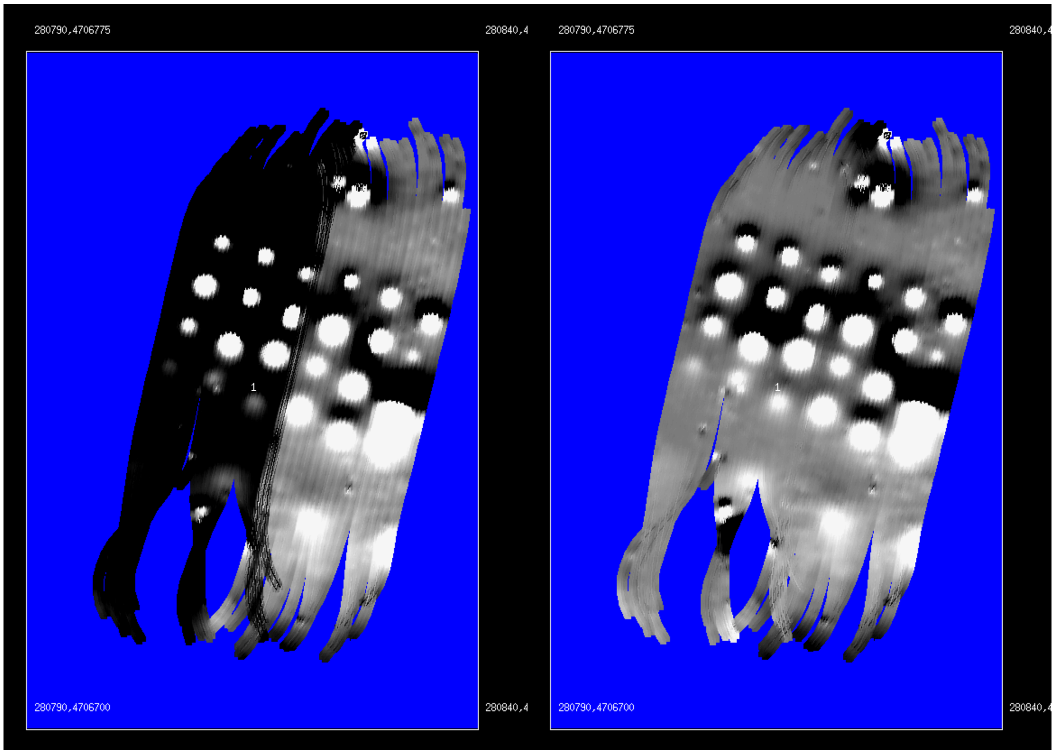


**Figure 6: Polaris Ranger, 10' Separation, Directionally Divided (left) and corrected to remove streaks (right), +- 50 nT**

There are two downsides to this technique. Firstly, note the darkening color and appearance of streaks at the ends of the traverses, particularly those in the southeast corner, indicating that the correction is breaking down where the vehicle direction is changing. Vehicle traverses have to be of very uniform direction for this to work well. When driving around typical obstacles like trees, or having an accumulated “bow” in a survey line, it is common for that section of data to be streaky even after correction. Second, because of signal differences in the different regions where the operator selects the areas of interest to calculate the offsets, the different directions always emerge from the correction with different gross background values, and the analyst must manually match them up at their edges. Matching up the edges of the patchwork quilt becomes particularly challenging in irregularly-shaped areas with, for example, WE traverses that impinge on a predominantly NS survey. But for small areas, or areas with very regular traverses, directional dividing works quite well.

### Time-Series (Median) Filtering

A technique pioneered by personnel at the former AETC working with MTADS data is to use a median filter to calculate the median value of a five to ten second window of data, and then subtract that value from the data. This essentially acts as a low pass time series filter on the data, and is highly effective in excluding signals that change relatively slowly over time. The appealing thing about this technique is that, in addition to filtering out effects of the vehicle, it also filters out diurnal drift of the Earth’s magnetic field, long-wavelength geology, and even the “corduroy” in the images due to small intersensor

offsets. In addition, unlike the directional dividing technique that requires the analysts' interaction to correct and match up the pieces, the median filter is turnkey. A downside of the technique is that the data can "ghost" when signal from a strong object gets into the six-second window, qualifies as a median value, and is subtracted off. This can happen in areas dense with anomalies when the algorithm is confused about what constitutes background. The time window can be lengthened to reduce this effect, but this also reduces the median filter's ability to react to changes in the data that you wish to filter out (e.g., the changing vehicle signature with changing orientation).

The left image below is the unfiltered data from the Polaris ranger 10' back, and the right image is after a six-second median filter has been applied and subtracted from the data.

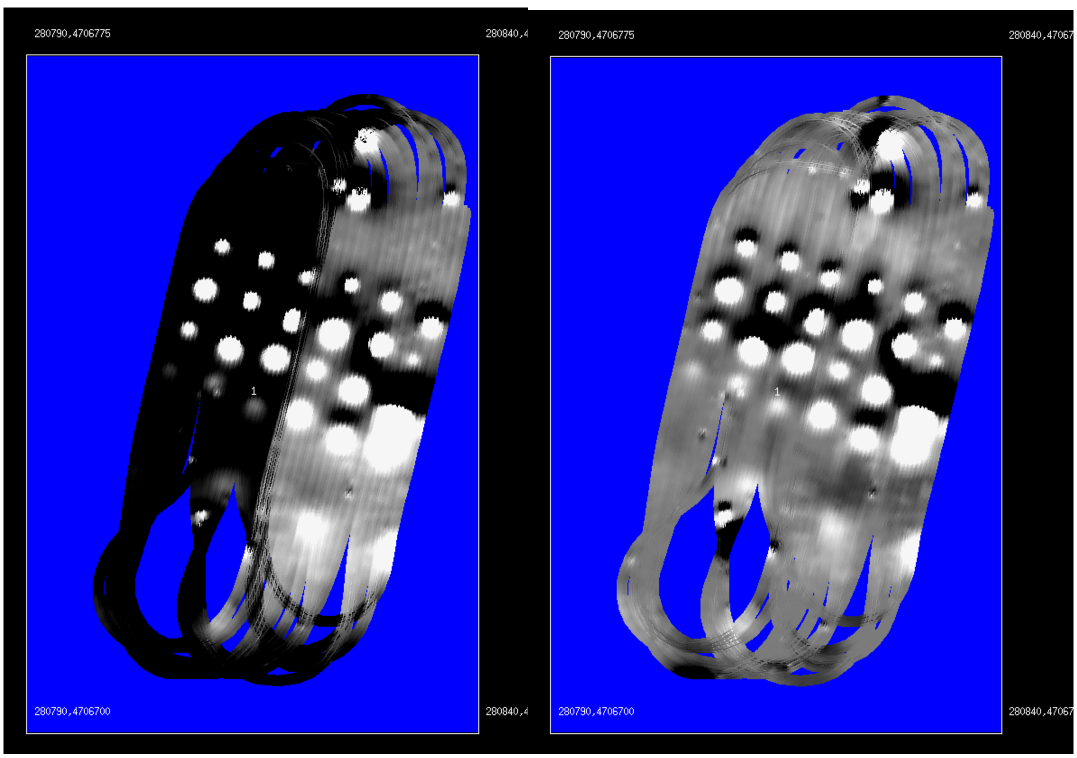


**Figure 7: Polaris Ranger, 10' Separation, Unfiltered (left) and Median Filtered (right), +- 50 nT**

The median filter does a fairly nice job on this 10' data, even tracking the background most of the way around the tight turnarounds, but there are "clouding" artifacts in the north part of the image that are not present in the directionally divided data above. We believe that this is a function of the highly aggressive 10' vehicle-to-magnetometer separation and of the high density of objects. The small area and tight geometry of the Devens test site plays to the strengths of directional dividing, and consequently plays against the strengths of median filtering. Median filtering works extremely well on moderate to large sites, and as said above, also removes diurnal drift and long-wavelength geology. We will show an example using a larger set of data at the end of this document.

As with most filters, the time window used for median filtering is a tradeoff between what you want to exclude and what you wish to preserve. The shorter the window, the more responsive it is to fast changes in the data, but these fast changes include the very MEC objects we wish to detect, raising the risk of filtering out valid signal. The longer the window, the less likely it will filter out valid signal, but if the window is too long, it won’t suppress the changes in vehicle signature due to changes in heading. Trial and error have shown that six seconds is a good middle ground, filtering out nearly all vehicle signature and engendering only minor artifacts when running over dense packs of objects. We show this below.

As said above, 10’ is a very aggressive vehicle-to-magnetometer separation, so to show the effect of varying the length of the median filter window, we use the 15’ Polaris Ranger data, as 15’ is the realistic separation currently employed in VSEMS (MTADS uses 16’). In the ten images below, the median filter window is varied from 1 second to 10 seconds. The shortest windows (1 and 2 seconds, below) clearly distort the anomalies.

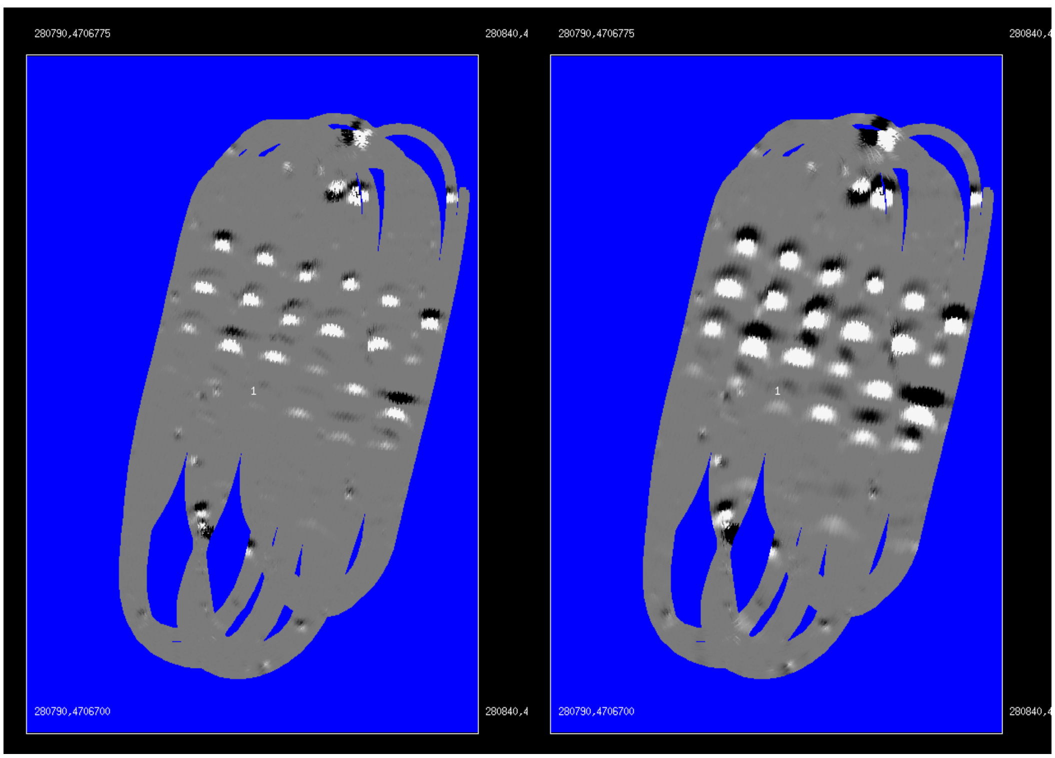


**Figure 8: Polaris Ranger, 15' Separation, 1 Second (left) and 2 Second (right) Median Filter, +- 50 nT**

Most of the anomalies in the data created with the 3 and 4 second windows below look reasonable, but on closer examination, the larger broader anomalies from the deeper object in the southern part of the test site (highlighted in yellow square) have lost signal as compared to the longer 5 and 6 second windows. The green square is an area where the vehicle is turning around with a very tight turning radius, representing a very fast rate of change for the signature. An artifact (a dark shadow) is growing in this area, and continues to grow in the longer windows on subsequent pages.

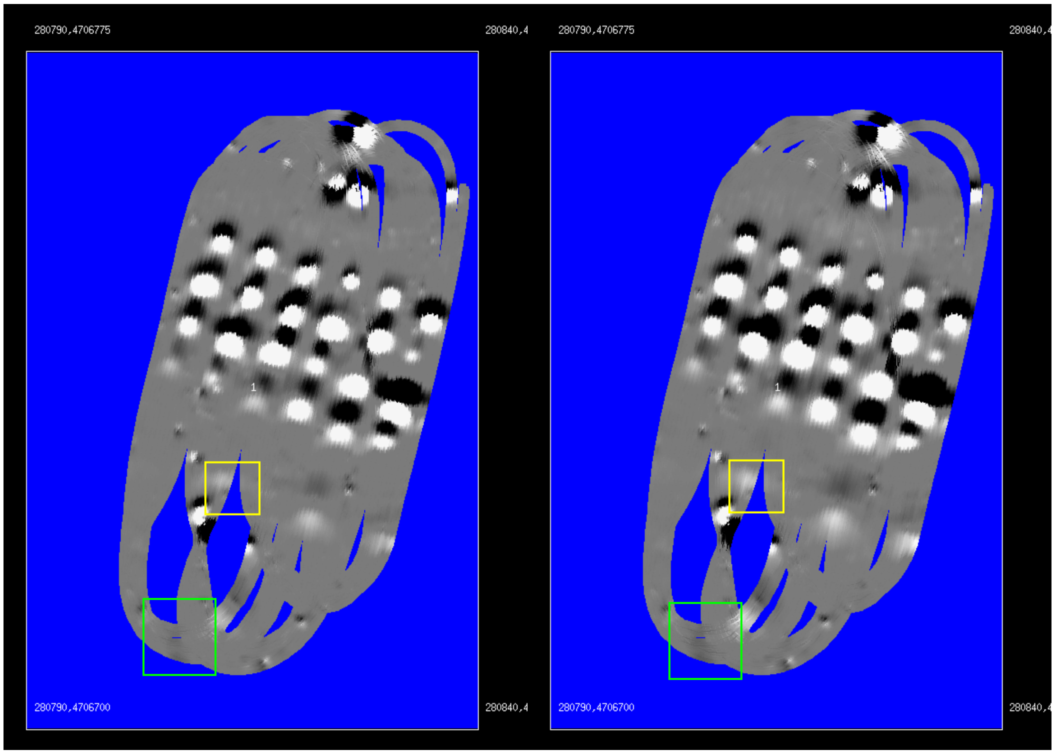


**Figure 9: Polaris Ranger, 15' Separation, 3 Second (left) and 4 Second (right) Median Filter, +- 50 nT**

In the two images below with 5 and 6 second windows, the window is long enough that the deep object highlighted in yellow is relatively unaffected, but the filter window is now longer than the time required to respond to and filter out the turnaround at the south end of the site (green rectangle). This effect is exacerbated in these Devens images because the site is small and because we were running a “racetrack” pattern that leaves the turnaround in the data set. On most surveys, the turnaround would either be outside the area, would be chopped out, or would not be so tight.

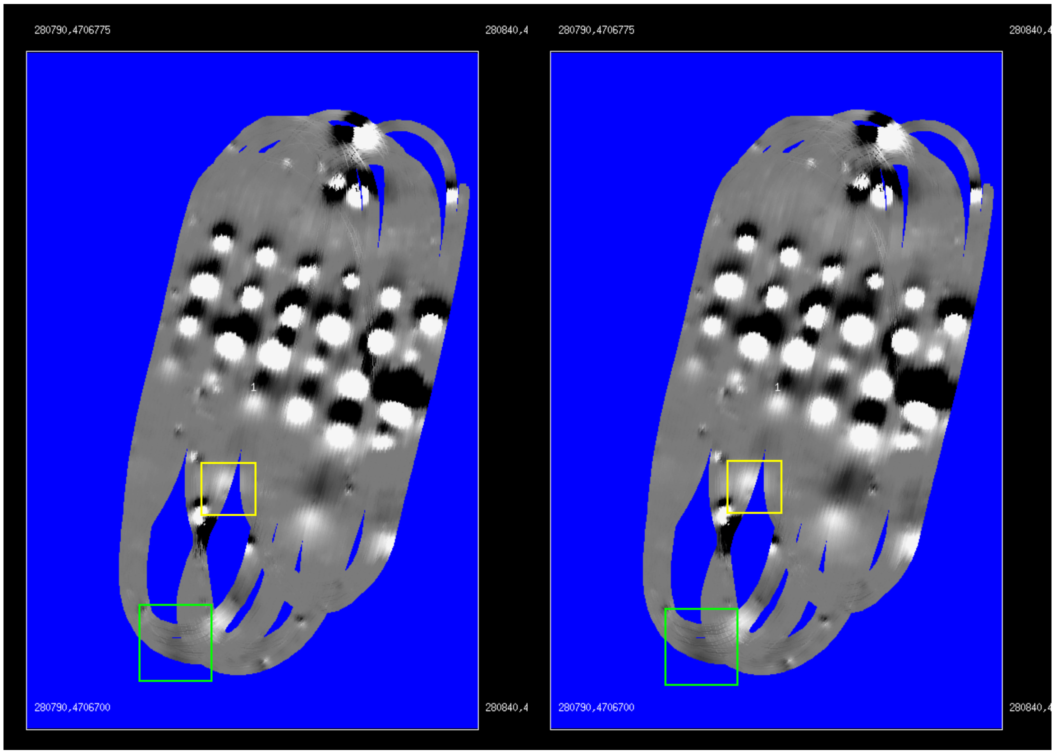


**Figure 10: Polaris Ranger, 15' Separation, 5 Second (left) and 6 Second (right) Median Filter, +- 50 nT**

In the images below, generated with 7, 8, 9, and 10 second windows, the deep MEC simulant in the yellow square does not grow in intensity as compared to the 6 second example, but the shadow artifact from the turnaround in the green square does get worse. For this reason, we usually use a 6-second window on our median filter to remove the remnant vehicle signature.

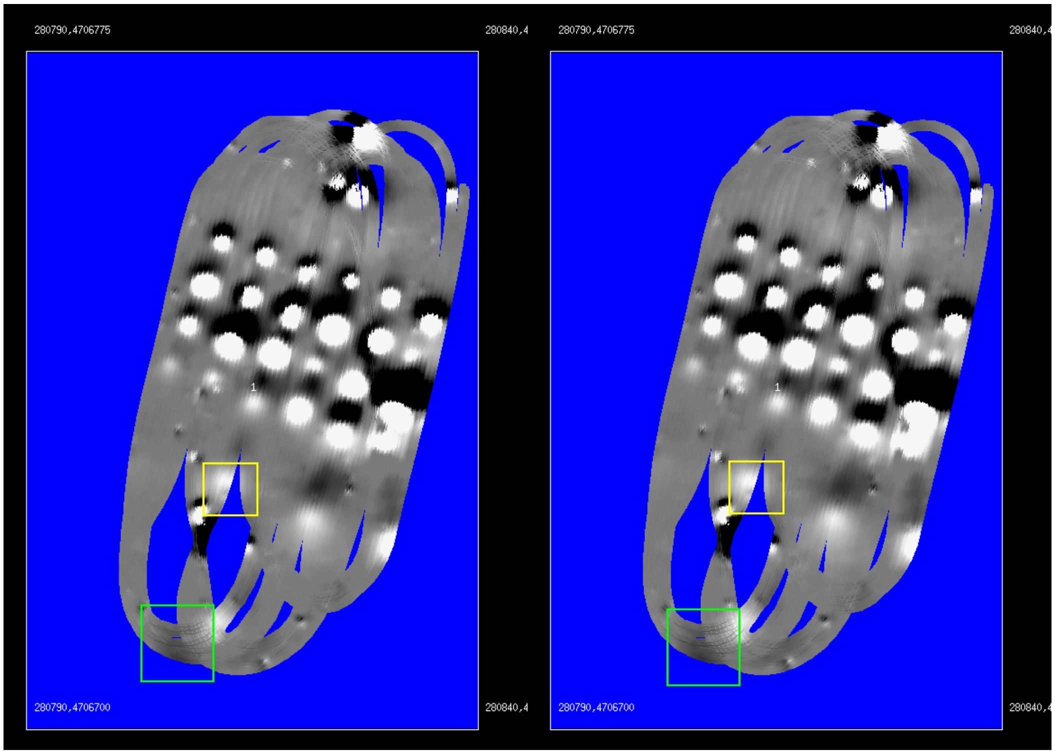


**Figure 11: Polaris Ranger, 15' Separation, 7 Second (left) and 8 Second (right) Median Filter**

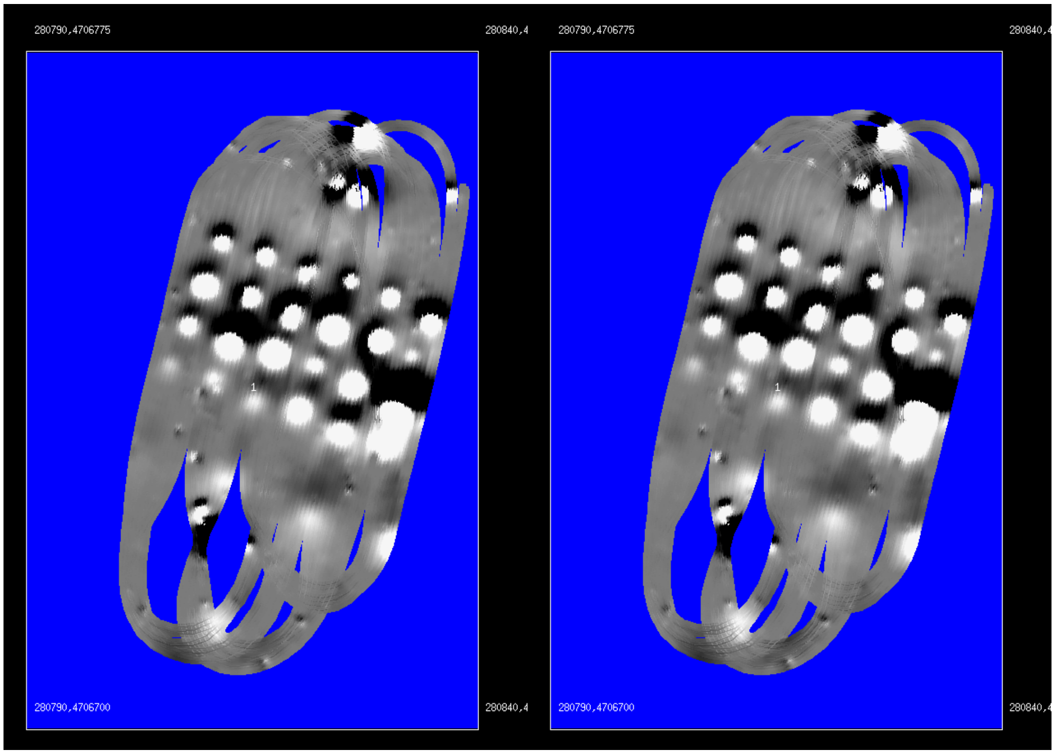


**Figure 12: Polaris Ranger, 15' Separation, 9 Second (left) and 10 Second (right) Median Filter, +- 50 nT**

Finally, to give a fuller picture of the use of median filtering for vehicle signature removal, below we present three images created using VSEMS data taken in 2004 over the 13-acre open field at the APG test site. Because this is a much larger area than the Devens test site, requiring traverses in several different directions, it shows off the advantages of median filtering. *Note that we are intentionally showing data that is not of the highest quality in order to showcase the utility of the median filter.* In 2004 VSEMS was still using its prototype fiberglass platform originally developed in 2002. This platform had the magnetometers in the middle of the platform, only 10’ behind the vehicle, and the EM61 coils in the back (these locations have been swapped on the new platform). In the first image below, we clearly see the streaking caused by the vehicle signature.

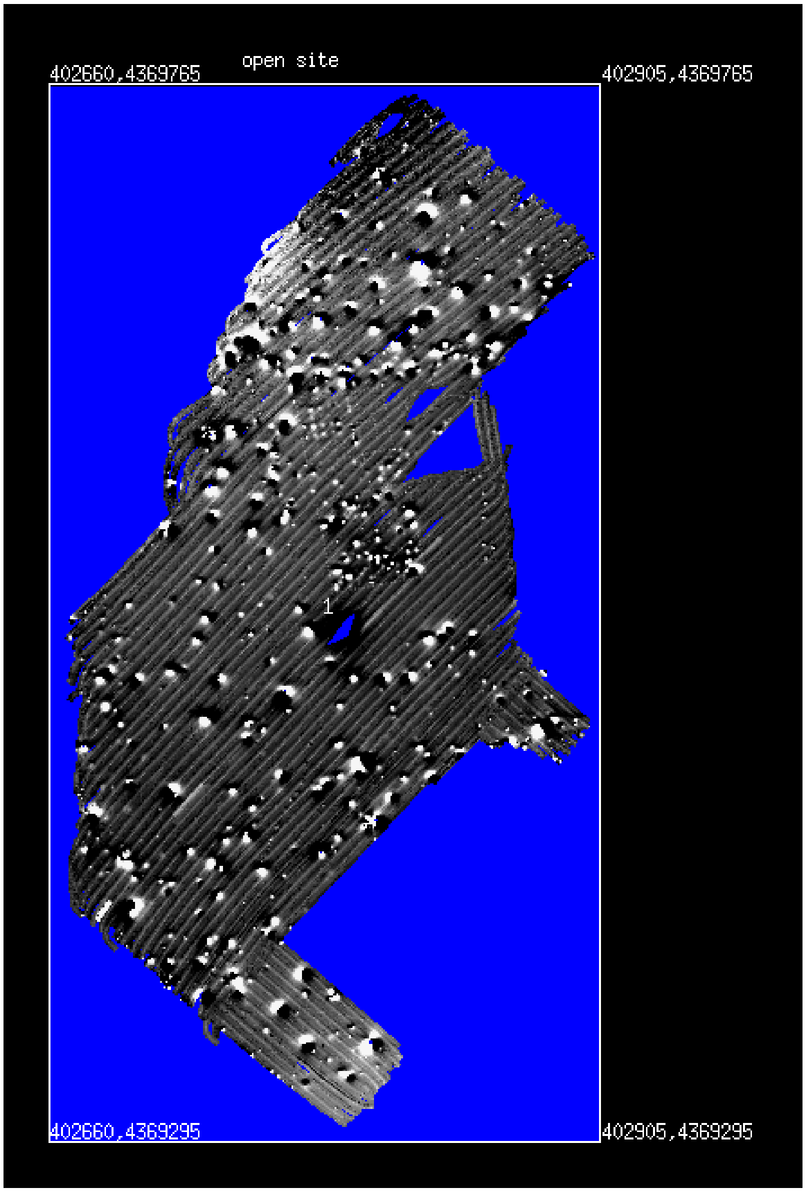


**Figure 13: Unfiltered VSEMS Data, APG Open Field, 2004, 10' Separation, +- 50 nT**

The next image was created using the directional dividing method described above. To create this image, all NE, NW, SE, and SW traverses were segregated and corrected individually. Most but not all of the streaks have been removed. However, in these data, there is a source of noise (eventually determined to be from a ground loop) that creates streaks in the data that are not constant for a given direction of travel. Because the directional dividing technique uses *static* offsets for each directional set, it can not compensate for time-varying effects such as these streaks.

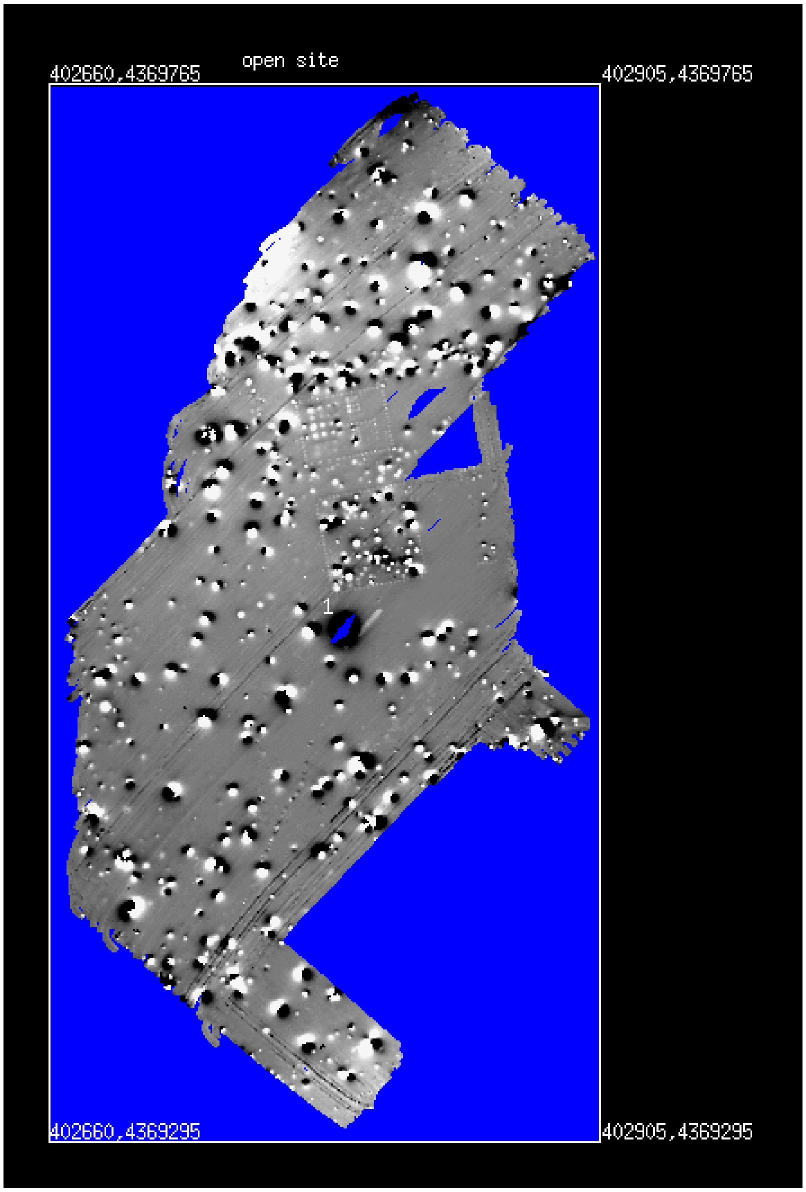


**Figure 14: Directionally Divided VSEMS Data, APG Open Field, 2004, 10' Separation, +- 50 nT**

In the last image, we median-filtered the data using a five-second window. Since the median filter is dynamic, it was able to address most of the remaining streaks. The median filter also has removed the geologic "bloom" along the western edge of the data set. These data are in fact slightly over-filtered, with some visually apparent loss in signal. In 2004, when these data were acquired and initially processed, after examining this filtered data set, we increased the default median filter window value from five to six seconds, where the default value remains for our processing today.

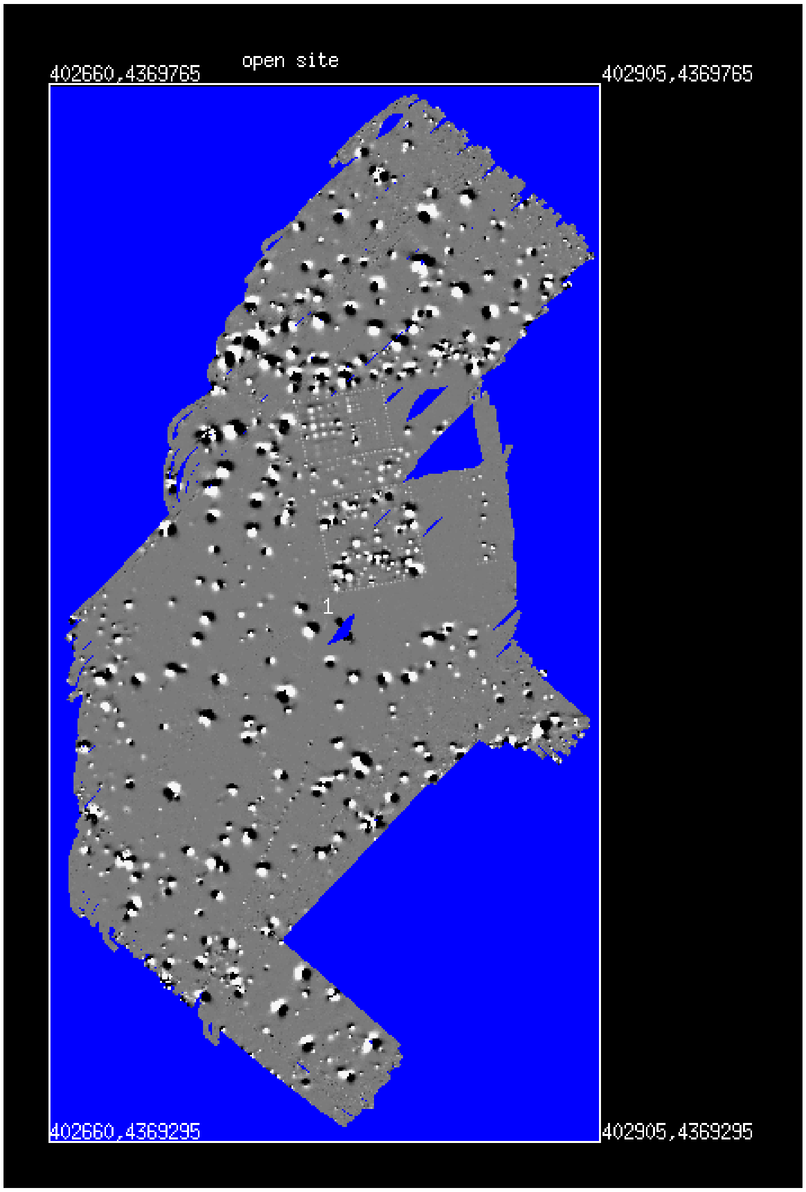


**Figure 15: Median-Filtered VSEMS Data (5 second Window), APG Open Field, 2004, 10' Separation, +- 50 nT**